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6. AUTHOR(S)
Gilead Tadmor and Aleksandar Stankovic

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Northeastern University
Boston, MA 02115

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13. ABSTRACT (Maximum 200 words)

The use of energy dynamics / dissipative design is one unifying theme for the various projects carried under this grant, exploring the scope of quadratically dissipative design, design based on shaping Hamiltonian dynamics and design for systems with non-quadratic energy structures. Specific projects involved the permanent magnet synchronous, switch reluctance, induction and DC motors, power electronics devices, including a three phase synchronous rectifiers, the series resonant converter, voltage source inverters, and power distribution systems. Projects involving electric motors ranged from a basic dissipativity based controller, to modeling and adaptive attenuation of torque ripple, and observer based shaft sensorless control for dynamic speed tracking. Concepts of nonlinear dissipative control and observer design were also studied in a fluidic turbulent system that features non-quadratic non-linearities and Hamiltonians.

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electric motor drives, dissipative & energy based nonlinear control, position sensorless control, adaptive torque ripple attenuation, dynamic phasor models, power electronics and power systems control.

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Summary of Results

1 Control of a Permanent Magnet Synchronous Motor (PMSM)

1.1 *Energy Based PMSM Control*

The emphasis in our work in basic PMSM control was fourfold: the development of design methods that are directly targeted at improved performance relative to specific, practical criteria, was one goal; an improvement in the design procedure itself, with an emphasis on an orderly selection of both controller structure and design parameter, and the avoidance of lengthy trial and error cycles, was a second goal; a flexible structure that allow seamless add-on components, such as adaptation, was the third goal; finally, our research also aimed at gaining theoretical insight into a family of dissipative / energy-based design methods, that prove to particularly useful in motor drive control, as well as in the wider area of control in power engineering. Work on a controller based on a quadratic storage function was completed prior to the award of this grant (see [DST97]), and formed the foundation of much of our subsequent results on PMSM control during the reviewed period.

An alternative approach, based on the wider scope modeling paradigm of Port-Controlled Hamiltonian Systems was developed in [POS99, POS00a, POS00b]. Energy-based control design aims to shape a target energy function that is directly minimized in the closed loop system, at the desired trajectory. Our goal was to demonstrate the application of energy-based design methodology to PMSM. The proposed controller guarantees global convergence and can be easily tuned to improve performance. Under standard practical assumptions it simplifies to a well known design methods.

1.2 *Modeling and compensation of torque ripple in a PMSM*

A significant structural cause for torque ripple is the deviation from perfect sinusoidal flux curves. Cogging torque ripple occurs at higher frequencies and can be alleviated by structural modifications (e.g. by skewed stator winding). Imperfect flux curves result with substantial harmonics in the back EMF, stator currents and, eventually, in the produced torque. Including higher harmonic components in the flux model allows compensation with appropriate modulation of the applied voltage, to remove torque harmonics. One option to compute the necessary modulation is to rely on off-line estimates of the flux harmonic coefficients. An adaptive alternative is where the said coefficient are estimated on-line by a passive adaptor, based on current measurements. The adaptive controller is easy to implement and tune, and experimental results are used to demonstrate its effectiveness. Preliminary results were presented in the conference papers [PST98, GCvS01] and comple results appear in the journal articles [POST00, GCvS02].

1.3 *Dissipative control of a dual inverter system*

Power requirements dictate the use of efficient, high power rated but slow switching inverters. Low swithing frequency results with induced current and torque ripple. The studied drive system comprises a parallel interconnection of a high power GTO and a low power, fast switching IGBT, which is used for attenuating the current ripple in the GTO. The challenge in both the basic control algorithm and a proposed space vector modulation (SVM) inverter switching algorithm is the delicate choreography of a master-slave operation of the drive, preventing excessive stray currents between the two inverters. Results are presented in submitted conference papers [Tad02a, Tad02g] and submitted journal articles [Tad02b, Tad02h].

1.4 *Shaft sensorless control of a PMSM.*

Several algoritmms have been developed in the course of this grant, which could be roughly grouped in two classes.

1.4.1 *Full state observer based algorithms*

A distinguishing aspect of the full state observer is that it does not require quasi steady state / time constant separation hypotheses, common in partial state observers. Experimental results include tracking step and sinusoidally varying speed references and a step change in the load torque. In our original algorithm, an inherent singularity at zero speed is manifested by observer gains that are reversely proportional to the estimated speed, a shortcoming preventing very low speed operation or direction changes. This was addressed in very recent development of observers for both the salient and the non-salient PMSM, based on local decoupling of speed and load torque estimation from angle estimation. The new method builds on an interesting observation whereby ohmic losses minimizing currents ("max torque per ampere") appear to be associated with an inherent motor geometry. That geometry is used to decouple observer structure in a way that error dynamics of speed and load estimates are locally decoupled from angle estimates and remain stable at zero speed. The remaining *soft singularity* in angle estimation is then manifested only in a degeneration to an uncompensated, marginally stable integration of the speed estimate. In the salient case, adverse ripple effects of harmonic injections, used to stabilize low speed position estimation, are also markedly reduced by use of the said geometry. Consequently, the difficulty in low speed operation and direction changes is reduced, if not altogether eliminated. Results are presented in conference papers [TJPS00, Tad02f, Tad02c], and in the full manuscript [TJS02]. that we currently prepare for journal submition.

1.4.2 *Sensorless PMSM Control Based on Current Ripple & Saliency*

This line of research produced [POS01, RO00, PS01a, PVRS01, PS01b] a position and speed estimation algorithm based on magnetic saliency of PM synchronous motors. The proposed method uses inherent high frequency content of motor PWM excitation to measure position dependent inductance parameters, which are then processed using a simple nonlinear observer to produce the position and speed estimates. To ensure persistent excitation at all operating voltages (speeds), a novel PWM algorithm with full voltage output is developed and presented. The efficiency of the modified excitation was evaluated and compared to the efficiency of the standard position–sensorless motor drive excitation. Experimental results are presented as well, showing good algorithm performance in a wide speed range, including zero, and for various load torques.

We also analyzed effects of selection of injection frequency on performance of position–sensorless algorithms for permanent magnet synchronous motors (PMSMs). The sensitivity with respect to the rotor position of the transfer function between the injected quantity (e.g. voltage) and its response (e.g. current) is explored over a wide frequency range, yielding analytical results that optimize the selection of injection frequency in terms of motor and drive parameters. The frequency selection procedure is based on motor parameters that were obtained in laboratory tests. Numerical simulations and experimental tests of a position estimation algorithm were performed as well, yielding results that support findings of the sensitivity analysis.

1.5 Control of a PMSM under angle-periodic load

Common examples of angle-periodic loads include pumps and compressors. Such loads might cause substantial mechanical harmonics with potential adverse effects on both the system's structural integrity

and its performance. Standard PI controllersimplicitly assume a constant load and will compensate mainly for the dc its component. Compensation for angle-dependent harmonics will then require aggressive gains and wide closed loop bandwidth, with such adverse effects as the amplification of noise and of unmodeled flux-harmonics. The purpose of this study is to extend our previously developed passivity based controller to include adaptation on load harmonics. Specifically, the load is modeled as a truncated Fourier series in the mechanical angle, and adaptation is with respect to the leading Fourier coefficients. A challenge that arises in this setting, when compared with design for a constant load, concerns a systematic procedure for the selection of design parameters. Error transients in the standard, constant load case, are governed by an essentially LTI system, and design parameters can be guided by eigenvalue / time constant assignment, where the goal is to cluster all closed loop time constants, assuring the fastest response with the narrowest bandwidth. The LTI structure is lost when harmonic adaptation is added, where even near steady state linearization produces a periodic, LTV system. Our initial approach is to launch an optimization search, using on Floquet analysis and initial guesses based on insight gained into expected deformations of selections for the constant gain case. These results are summarized in a Masters project report [Eis01].

2 *Adaptive Torque Ripple Reduction in Switched Reluctance Motors (SRMs)*

Torque ripple is a major impediment to wide spread use of SRMs. These motors are driven into magnetic saturation in standard operation, and a major cause for torque ripple is the use of crude, almost model free, square wave based controllers. The reason for avoiding more sophisticated compensation is the difficulty to obtain a practically simple and adequately accurate model for their flux curves. Early work [JSTC95, STC96, JST95, STCA99] begun prior, and completed during the period covered by this grant, concerned a parameterization of controller, based on an available degree of freedom in current waveforms, and a utilization of that degree of freedom to suppress torque ripple while minimizing currents supply requirements.

Our subsequent research focused on the development of an adaptive, torque ripple minimizing control design method. The underlying principle in this method is to avoid the need for an elaborate, off-line computed model. Instead, the starting point is an extremely simple and obviously inaccurate representation for torque dependence on current and stator position: this representation postulates a linear dependence of torque on current and a sine function dependence on position. The resulting steady state torque ripple will be periodic and dominated by a few harmonic coefficients; it is viewed by the compensator as an added load component. Both the dc component of the load torque and its main harmonic coefficients are dynamically estimated, and applied phase currents are modulated accordingly. The result is the removal of leading torque ripple harmonics. The method was experimentally validated. Preliminary results, predating this grant, appeared in [AST98a, AST98b, ATS99, ATSLA01].

3 *Analysis and Experimentation with Adaptive Controllers for the Series Resonant Converter*

Here we explore the problem of regulating the output voltage of a DC–to–DC series resonant converter (SRC). These converters have highly nonlinear dynamics fed by a bipolar square signal generator whose commuting frequency is the only accessible control variable in the control architecture that we study. Therefore, we are confronted with the problem of controlling a nonlinear switched system by means of a modulating frequency signal. Two more complications that make this problem more challenging are that the full state is typically not available for measurement, and that the output load, usually represented by a resistance, is unknown. We show here that –for constant control input– SRCs have a unique globally attractive periodic orbit, which motivates us to consider a first harmonic approximation of the system. We then prove that this reduced model consists of a known static nonlinearity in cascade

with a first order system with unknown parameters, for which adaptive output feedback solutions can be derived. We propose two different schemes, first a passivity–based controller which, as usual in these schemes, achieves asymptotically the inversion of the nonlinearity. We prove that, under some practically reasonable considerations, this control law reduces to the dissipative controller recently proposed by Stanković *et al.* The second scheme directly inverts the static nonlinearity and applies standard adaptive techniques to the resulting linear system. The three controllers are implemented in an experimental setup and the results are presented as a comparative study. Related publications include [CGE+00a]

4 *Passivity-Based Controller for Harmonic Compensation in Distribution Lines with Nonlinear Loads*

Here we explored a passivity–based control for active power filters that are used not only for the compensation of specific thyristor or diode rectifiers, but also for more general loads. Such loads may include, for example, power factor capacitors or may have unknown dynamics. To provide an alternative to existing solutions, which often lead to unstable operation in demanding applications, we investigate the effectiveness of a family of passivity-based controllers using on frequency-domain modeling of the system dynamics. Following the passivity-based design procedure, we first obtain a compensation strategy that allows stable active filter operation regardless of line and load parameter variations. Secondly, to ensure precise tracking for the selected harmonics, we develop an adaptive procedure which allows (under varying degrees of approximation) to estimate line and load parameters. Finally, a comparison with a linear controller suggested by our passivity-based control structure shows the advantages of the proposed solution. Simulation results are presented which confirm effectiveness of the proposed controller.[SEM00a]

5 *Reactive Power and Unbalance Compensation Using STATCOM with a Dissipativity-Based Controller*

We investigated the use of dissipativity-based control for voltage sourced inverters (VSI) applied as reactive power and unbalance compensators, such as STATCOM's. The pproach relies on a frequency domain modeling of system dynamics using both positive sequence and negative sequence dynamic components. The proposed approach can deal with unbalanced supply voltages and perform regulation of ac unbalanced currents, even for those VSI inverters where, due to switching frequency limitations, stationary frame regulators do not have enough bandwidth to cope with reference tracking . The passivity-based procedure is investigated in terms of adaptive terms, anti-wind-up limitations and decoupling between the dc-link and ac current regulations, together with stability and convergence proofs. Finally, the paper explores a sequence of simplifications and adjustments that reduce the adaptive controller to PI structures with feedforward for positive and negative sequence components, thus establishing a downward compatibility with standard industrial practice.[ESM00a, SEM00b, ESM+00b].

This line of investigation continued with a study of reactive power, harmonics and unbalance compensation. using STATCOM with a dissipativity-based controller. Here we present a solution to the problem of reactive power compensation and harmonic compensation in the general case when *both* the source voltages and the load currents are unbalanced and contain an arbitrary number of harmonics. For the compensation purpose, a D–Statcom is connected in parallel to inject the required currents, so that from the source terminals the *same* apparent resistance is observed in all phases and at all frequencies. A controller based on the ideas of passivity theory, to which we have added adaptation to compensate for the unavoidable uncertainty in some of the parameters, is suggested as a solution. One of the major advantages of this solution compared to conventional ones is that we are able to per-

form precise tracking (also for high order harmonics) even in the presence of a relatively low switching frequency, i.e., in presence of an active filter with limited bandwidth. Simulation results are provided to illustrate the performance of our controller.[EMS01, MES01a]. Furthermore, related results were devloped for three-phase uninterruptible power supplies (UPS) in [MES01c, MES01b].

6 *Passivity–Based Controller for a Three Phase Synchronous Rectifier*

A passivity–based control (PBC) law, previously addressed as nested–loop PBC, is considered. We have added a sliding mode control (SMC) scheme for the design of the switching control sequence of a three phase Boost type rectifier. The controller presented here is indeed a modification of the original PBC scheme, which was necessary in order to eliminate bias components that appear in the input currents, which may cause possible saturation in the magnetic elements. Also, a justification for the PI external loop extensively used in implementations is given here. The proposed controller was implemented in an experimental test bench.[CGE+00b]

7 *Modeling and Analysis of FACTS Devices with Dynamic Phasors*

This project concerns the use of dynamic phasors in modeling and analysis of FACTS, and illustrates the capabilities of the methodology on Thyristor-Controlled Series Capacitors (TCSCs) [ESOM02, ESOM02] and on Unified Power Flow Controllers (UPFCs) [SS02, SS00]. The large signal phasor models of these subsystems are expressed in continuous time, making them directly compatible with the conventional models used for the other system components.[]

The papers describe [SS02, SS00] an analytical large-signal model for unbalanced operation of the unified power flow controller (UPFC). This nonlinear, time-invariant model is expressed in terms of dynamic symmetric components, and it is validated on a benchmark power system example taken from the literature. The model is evaluated via simulations in unbalanced operation and during unbalanced (one phase to ground) faults. In both cases, it achieves a very good accuracy, in addition to a reduction in simulation time when compared with detailed time-domain models. Index Terms-Dynamic phasors, dynamical models, flexible ac transmission systems (FACTS), unbalanced conditions, unified power flow controller (UPFC).

The papers [ESOM02, ESOM02] review modeling of thyristorcontrolled series capacitors (TCSC) which are highly nonlinear systems with continuous and discontinuous states, and proposes three nonlinear controllers for it: (1) An approximate feedback linearization control (FLC) (2) A sliding surfacelike design (3) Control in transformed coordinates. Detailed (switched) timedomain simulations are used to verify the control performance a chieved by the three controllers.

8 *A Study of the TORA Benchmark*

The issue of parameter selection is substantially more complex in nonlinear design frameworks, such as in the dissipative/energy-based control we use in our work on electric motor drives, then in linear systems. Qualitative guidance is provided, in our approach, by the need to create lossless power exchange between control-accessible and control-inaccessible states, and to balance the rate of such dynamics with dissipation rates. When the system operating envelope is relatively narrow, quantitative parameter optimization can be effectively guided by an analysis of near-steady-state linearization. An example of a simple consideration here might be pole/time-constant placement. . This was demonstrated, e.g., by our work on PMSM control. The project described here, however, aimed at exploring the issue of dissipative controller's parameter assignment and, indeed, controller structure selection, for nonlinear systems operating during large deviations, away from steady state. The TORA benchmark example

was used as a test case. The TORA system comprises a friction free linear oscillator mounted with an eccentric proof-mass actuator. It was introduced in 1995, has received considerable attention since (including dedicated conference sessions and journal issues), and was addressed by several teams. Many of the suggested designs have been of "dissipative" controllers, but most focused on near steady state design. Our preliminary analysis clearly demonstrated that parameter selection based on near-steady state optimization can be dramatically inferior during large deviation: indeed, in our example it required over 20 fold higher actuation, for an inferior performance, when compared for parameter tuned for large deviations, with the same controller structure. The explanation for this phenomenon is the fact that the relation between lossless and dissipative dynamics is substantially different during large oscillations than near steady state. A more detailed study further revealed that the very structure of the standard full state dissipative compensator (including the combined linear oscillator and proof mass), is inherently disadvantageous, during large oscillations. The reason is an inherent, absolute bound on power flow rate between the two subsystems. A consequence of that bound is the fact that majority of the actuation force is used to oscillate the actuator, and only a small fraction is actually used to dampen the "plant", which is the linear mass. An alternative dual mode compensator, which takes this inherent restriction into account achives improved performance, concurrently with a ten-fold reduction in the required actuation, meaning a 200 fold reduction in the required actuation, when compared with a standard dissipative controller, optimized at steady state. results are presented in [Tad99a, Tad99b, Tad01a]

9 *Dynamic Phasor Representations in Bilinear Dissipative Systems*

The dynamics of slowly varying Fourier coefficients (or phasors) of closed to periodic trajectories is governed by differential equations, obtained from a dynamic model of the original time domain system. While the use of a dynamic phasor representation is both intuitively motivated and strongly supported by numerous case studies, it lacks a solid theoretical basis, or even strong theoretical plausibility arguments. The purpose of this study is to explore such theoretical basis / plausibility arguments in the context of bilinear dissipative systems. This class of includes many standard models AC electric machines. On the one hand, quadratic nonlinearity poses a challenge, in the sense that systems are not uniformly Lipschitz continuous; on the other hand, this form is maintained under Fourier transform, where products are replaced by convolution terms. Dissipativity is used to ensure stability of both the time domain dynamics, phasor dynamics, and approximate phasor dynamics. Results pertain to the implication of well posedness of the original system in a neighborhood of a solution of the approximate phasor model, in both steady state and transient modes. Results are presented in [Tad01b, Tad02e].

10 *Dissipative Observers for Vortex Dynamics*

This direction of research continues our effort to gain insight into the use of Hamiltonian energy dynamics for control and observer design. The example of fluidic vortex dynamics in a combuster recirculation zone introduces the challenge of a highly non-linear dynamic model with a total Hamiltonian that consists of the sum of an indefinite quadratic component and a logarithmic component. A quadratically dissipative state observer can be derived in a local neighborhood of the rest point, and used as part of a dynamic tracking controller, in that neighborhood. Although the model includes no damping, we are able to develop a low-gain dissipative, hence stabilizing feedback control policy that requires only a vague knowledge of state location, based on oscillations of the relative weights of the two components of the total energy. This controller is used to drive the state from initial positions in the far field to the local neighborhood where it can be switched to the observer based controller. Results pertinent to this benchmark are presented in [TB02, TB01, NMBT02]. A subsequent study addressed a second

benchmark, comprising with the control of the 2D motion of a rotating vortex pair [Tad02d]. Again, the leading themes from our work on electric motor drives: passivity and the focus on phasor dynamics, play the key roles.

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